Magna Scientia UCEVA (2023) 3:1, 116-124
ISSN: 2805-6884 e-ISSN: 2805-6701
https://doi.org/10.54502/msuceva.v3n1a11

Reflection Research Article | *Agricultural and Biological Sciences*

Unraveling mosaic viruses in contemporary agriculture: In-depth insights on characterization, impact, diagnosis, treatment, and management

Desentrañando los virus mosaico en la agricultura moderna: Perspectivas profundas sobre la caracterización, impacto, diagnóstico, tratamiento y manejo

John Edinson Herrera Gálvez†* and *Felipe Bravo Osorio

Open Access

Correspondence:

johnhjaipur@gmail.com
Coordinación de Urbanismo Táctico. Alcaldía Local de Kennedy: Bogotá, Distrito Capital, Colombia.

First draft submitted: 01-12-2022
Accepted for publication: 27-05-2023
Published on line: 01-07-2023

Key words:

Agronomy; agriculture; mosaic; plants; virology; virus.

Palabras clave:

Agricultura; agronomía; mosaico; plantas; virología; virus.

Citation:

Herrera Gálves JE, Bravo Osorio F. Challenges in modern agriculture: understanding of mosaic virus, characterisation, impact, diagnosis, treatment and management. *Magna Scientia UCEVA* 2023; 3:1 116-124. *https://doi.org/10.54502/msuceva.v3n1a11*

Abstract

Mosaic viruses are a constant concern for the agricultural sector. They pose a real threat to both food and ornamental crops, causing huge economic losses and even threatening food security in many regions. In this article, we will present a general overview of these viruses: their characteristics, transmission mechanisms, effects on crops and available control methods. We will see that one of the main difficulties in dealing with mosaic viruses is their diversity and wide host range. In addition, the lack of effective treatment alternatives and the practical challenges of diagnosing different mosaic virus species require constant epidemiological vigilance to prevent their spread. We will first present a general characterisation of mosaic viruses as an informal group of viruses belonging to tens of different taxa. We will then review the main symptoms of mosaic virus infection (hence the name "mosaic"), diagnostic methods, host range, transmission mechanisms and treatment options. Secondly, we will discuss the impact of these viruses on ornamental and food crops. Finally, we will look at some possible strategies for infection management and control.

Resumen

Los virus mosaico son una preocupación constante para el sector agrícola. Representan una amenaza real para los cultivos, tanto alimenticios como ornamentales, y pueden llegar a generar pérdidas económicas millonarias y hasta a poner en riesgo la seguridad alimentaria en muchas regiones. En este artículo queremos presentar un panorama general de estos virus, sus características, medios de transmisión, impactos en cultivos y medios de control disponibles. Veremos que una de las dificultades fundamentales al enfrentar los virus mosaico es su diversidad y su extenso rango de posibles huéspedes. Además, la ausencia de tratamiento eficaz y los retos prácticas del diagnóstico de diferentes especies de virus exige un trabajo constante de vigilancia y seguimiento epidemiológico para evitar la propagación de virus mosaico. Empezaremos proponiendo una caracterización general de los virus mosaico como un grupo informal de virus pertenecientes a decenas de taxones diferentes. Luego veremos los síntomas característicos de una infección por virus mosaico (que le deben el nombre “mosaico”) así como los métodos de diagnóstico, el rango de huéspedes, los medios de transmisión y los posibles tratamientos. En segundo lugar, haremos una revisión del impacto de este tipo de virus en cultivos alimenticios y ornamentales. Y, por último, veremos las posibles estrategias de manejo y control de infecciones.

Introduction

Food security depends on a number of human, climatic, economic and epidemiological factors. 80% of human food comes directly from plants, not to mention their role in animal feed [1,2]. Plant and crop health must therefore be a constant concern for governments. One of the greatest current threats to the agricultural sector, and therefore to economic stability and global food security, is plant viruses. Each year, viral infections in crops are responsible for around $30 billion in losses [3,4] and more than 50% of the plant diseases in the world [5,6].

From this perspective, plant health should be a priority concern for both governments and all actors in the agricultural sector [7,8]. However, despite their importance and impact, the diagnosis, treatment and management of plant viral diseases represent a major challenge for the agricultural sector [9,10]. Some of the pathogens of greatest concern in this regard are the so-called "mosaic viruses", an informal and very diverse group of viruses with similar symptomatic characteristics that affect a wide variety of plant species [11]. Mosaic viruses cause hundreds of different plant diseases, causing millions of dollars in losses and posing a threat to food security, especially in developing countries [12,13].

Within this context, the aim of this contemplative analysis is to offer a comprehensive exposition on mosaic viruses. This entails delving into their fundamental characteristics, thoroughly assessing their substantial ramifications on crops [14] and elucidating the spectrum of accessible diagnostic and management methodologies. This endeavor seeks to unravel the intricate interplay between mosaic viruses and modern agricultural ecosystems, shedding light on their multifaceted influence and unveiling strategic pathways for effective intervention.

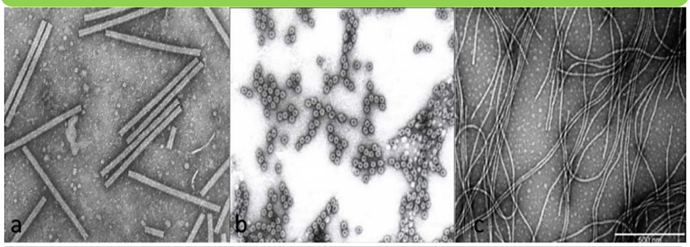
Diversity and impact of mosaic viruses

Characterisation

Mosaic viruses, although not directly related taxonomically, form a complex group of pathogens that affect a wide variety of plants with remarkably similar symptoms. The name 'mosaic' is derived from the mottled appearance of the leaves of infected plants. This viral conglomerate is defined by its manifestations and effects on crops rather than by its taxonomy per se. In fact, the term "mosaic virus" groups together about 150 viruses belonging to several different taxa.

These include single-stranded positive RNA viruses, such as those in the order Tymovirales, single-stranded negative RNA viruses, such as those in the order Bunyavirales, double-stranded DNA viruses, such as members of the family Caulimoviridae, single-stranded DNA viruses, such as those in the family Gemiviridae, and even satellite viruses, such as those in the genus Betasatellite. As a result, this category of viruses exhibits an astonishing diversity of characteristics in terms of genomic composition, virion structure, size, replication processes, propagation mechanisms and distribution patterns. The diversity of their characteristics defines a broad and complex field in which they operate, which is being addressed by several researchers [15-17] (see figure 1).

Figure 1. Diversity of virion structure in different mosaic virus species



a) Tobacco mosaic virus [18]; b) Cucumber mosaic virus [19]; c) Althernantera mosaic virus [20].

The best-studied virus in this group is probably tobacco mosaic virus (TMV), which has also played an important role in virological research [18,21]. In 1898, Martinus Beijerink first used the term "virus" to describe a pathogen infecting tobacco plants that was too small to be considered a bacterium. A few decades later, in 1935, VMT would be the first virus to be crystallised, in this case by Wendell M. Stanley - who would receive the Nobel Prize for his work in 1946. Since then, VMT, a mosaic virus, has become the model virus for research and the basic pathogen for much of the fundamental research and concepts in biology, medicine and agricultural engineering [21,22].

Today, mosaic viruses, along with other types of plant viruses, are the focus of intense research in virology, agricultural engineering and environmental studies. In fact, according to a survey of virologists, 5 of the 10 plant viruses currently considered to be of major scientific and economic importance are mosaic viruses [18]. Research has been devoted to better understanding their transmission and infection mechanisms, finding new diagnostic methods and developing effective treatments to reduce the risk they pose to the global economy and food security [12,13].

Symptoms and diagnosis

Given the diversity of mosaic viruses, symptoms vary greatly depending on the virus and the species infected. However, this informal group was formed precisely because of the observable similarities between the different infections. In general, infected plants develop yellow, white or green interveinal spots on their leaves, often in a mosaic pattern. Other symptoms include stunted plant growth, necrosis, roughness or deformation of leaves and other tissues, epinasty (curling of leaves) and discolouration of veins [23].

Symptoms tend to be more pronounced on young leaves. While mosaic viruses are usually not lethal to the infected plant, they can severely affect its growth, reproduction, and flower and fruit production [24]. In the case of food crops or ornamentals, this obviously means economic losses or food safety risks [25] (see figure 2).

Figure 2. Mosaic pattern characteristic of tobacco mosaic virus infection [18]

Asymptomatic infections have been reported for a large number of mosaic virus species. On the other hand, not all mosaic virus infections are considered negative. In some cases, mosaic viruses do not have a significant effect on plant growth and health beyond leaf spots, and some growers tend to grow and maintain infected plants for their ornamental value. An example of this is Abutilon mosaic virus, which affects plants of the genus Abutilon [26]. The variegation of the leaves resulting from infection is one of the main attractions of this plant (see figure 3).

Figure 3. Example of variegation in *Abutilon* sp. caused by Abutilon mosaic virus [27]

In some cases, it is possible to identify the genus or type of mosaic virus infecting a plant from its symptoms: this is the case for cassava mosaic viruses [25]. However, in general, due to the similarity of symptoms between different mosaic virus species, it is not possible to identify the type of virus responsible for a particular infection based on symptoms alone. In this case, further virological analysis, e.g. using monoclonal antibodies or PCR, is necessary. Furthermore, in agricultural practice, identification of mosaic viruses on the basis of physiological characteristics is not an easy task, as infection can be confused with other problems such as over-irrigation, pest damage, nutrient deficiencies or even variegation (see figure 4).

Figure 4. Typical symptoms of the mosaic virus

a) *Monstera adansonii* infected with Dasheen mosaic virus. The characteristic mottled pattern of the mosaic virus can be seen, as well as leaf deformations; b) *Monstera adansonii* variegated [27]; c) Monstera adansonii with yellowing due to irrigation problems or nutrient deficiency [28].

Infected species

Generally, a particular type of mosaic virus is named after the first plant species in which it is discovered: "Tobacco mosaic virus was first discovered in tobacco. This does not mean, of course, that these viruses cannot infect other plants. In fact, mosaic viruses infect a wide variety of plant species, both monocots and dicots, and both ornamental and food crops. For example, VMT infects about 125 plant species in nine different families. These include both ornamental and food crops, including several species in the Solanaceae and Cucurbitaceae families [29]. Another important example is Cocombrosis mosaic virus (CMV), which can infect more than 1000 plant species, including ornamental and food crops in the Fabaceae, Asteraceae and Brassicaceae families [30].

Transmission

The vectors of virus transmission are as diverse as the mosaic viruses themselves. On the one hand, plant-to-plant transmission is common, either by direct contact or by mechanical transmission by humans during agricultural work (e.g. through infected tools). Viral particles can be transferred from one plant to another by entering through tissue surface lesions caused by insects, fungi or mechanical damage [31].

Pests are one of the most important vectors of mosaic viruses. Beetles, aphids, whiteflies and other sap-sucking insects (order Hemiptera) can be important vectors of several mosaic viruses. For example, CMV is transmitted by more than 80 species of aphids [30]. On the other hand, mites of the family Eryophidae transmit wheat streak mosaic virus infections; and certain nematodes (only in the families Longidoridae and Trichodoridae) serve as vectors for some mosaic viruses, in particular Arabis mosaic virus, which is responsible for infections in strawberry, hop, beet, celery and lettuce crops, among others [32]. Finally, there are fungal vectors. This is the case of mosaic viruses of the genus Bymovirus (such as oat mosaic virus, rice mosaic virus and some wheat mosaic viruses), which are transmitted by rust (Puccinia graminis) in the soil [33].

Vertical transmission is also possible, depending on the virus species. In the case of CMV and other mosaic viruses of the genus Tobamoviorus, a mother plant can produce virus-infected seeds [34]. In other species, evidence for vertical transmission via pollen from infected plants has been found: this is the case for cucumber green marbled mosaic virus and peach latent mosaic viroid [35]. This diversity of mosaic virus vectors, combined with highly effective infectious properties, makes mosaic viruses a growing concern. For example, VMT and other mosaic viruses of the genus Tobamovirus are among the most stable and infectious viruses known [18].

Treatment

There is no treatment for any of the mosaic viruses. Management is therefore based on prevention, the use of resistant species and general good environmental practices. In the event of infection, each infected plant must be isolated and destroyed to prevent spread. The possibility of composting plant material or reusing the same soil where an infected plant was located depends on the particular mosaic virus species, but in general it should be avoided to prevent further infection.

Impact on crops and ornamentals

Research will focus on gaining an in-depth understanding of the impact of mosaic viruses on plantations worldwide. One of the major challenges associated with the spread of these viruses is their impact on crops of vital economic and food importance. The importance of this issue is accentuated by the wide diversity of viruses and the variability of possible host organisms, resulting in a wide range of plant species susceptible to infection. These include major food crops such as alfalfa, tomato [36], potato, rice, cucumber and wheat.

The direct consequence of mosaic virus infection is the generation of plant deformities, dwarfing of plants, alteration of their natural pigmentation and abnormal formation of apical buds. These effects are clearly detrimental to the quality and quantity of agricultural production, as pointed out by Tun Suarez et al. [37]. Agriculture is affected not only in terms of yield, but also in terms of marketing and staple food supply, underlining the urgency of addressing this issue in a comprehensive manner.

The impact of mosaic viruses goes beyond food production, as they also affect ornamental horticulture. The diversity of plants used for ornamental purposes is also exposed to the damaging effects of these viruses, directly affecting the aesthetics of parks, gardens and urban green spaces. It is therefore essential to understand the complexity of these effects in order to develop effective strategies to mitigate the economic losses and visual disruption caused by the presence of mosaic viruses in a wide range of plants, whether grown for their food or decorative value.

An example of the impact of mosaic viruses is the bean golden yellow mosaic virus. This virus affects perhaps one of the most typical and traditional foods of the American continent: beans (*Phaseolus vulgaris* L.); and has been affecting crops for more than 5 decades, causing agricultural emergencies in the region. Bean golden mosaic virus (BGMV) belongs to the genus Begomovirus (family Geminiviridae). It first appeared in Brazil in 1965 and spread with the rapid expansion of soybean cultivation. Although most soybean (*Glycine max* (L.) Merr.) varieties are not susceptible to Golden Yellow Mosaic Virus, this crop is a host to the whitefly (*Bemisia tabaci*), the main vector for the spread of the virus [38]. In this way, the virus spread rapidly in regions of Bolivia and Argentina, causing losses of more than 50% and severely damaging the capacity of the agricultural sector and even the ability of families to feed themselves [39] (see figure 5).

Figure 5. Symptoms of bean mosaic virus on bean plants [38]

Another very important crop in the family food basket, as well as in the agricultural and industrial sector, that has been severely affected by various mosaic virus species is maize. Maize is the third most important crop in the world and is host to around 50 virus species, including maize mosaic virus (MMV), sorghum mosaic virus (SrMV), sugarcane mosaic virus (SCMV) and maize dwarfing mosaic virus (MDMV). SCMV and MDMV in particular have a global distribution and are responsible for epidemic outbreaks and major economic losses. Both belong to the Potyviridae family and are mainly transmitted by aphids. Since the 1960s, MDMV alone has been responsible for losses of up to 70% in maize crops worldwide. MCSV affects not only maize but also the world's largest agricultural crop, sugar cane. Its distribution is global and has threatened the very continuity of the sugar cane industry in countries such as the United States, Argentina and Australia [40,41].

Another very clear example of chain infection is tomato mosaic virus, itself a member of the Tobamovirus genus, which can invade both the skin and even the embryo or internal seed tissue. This pathogen is widespread throughout the world and causes damage to tomato crops, both in greenhouses and outdoors, as well as to other Solanaceae crops. This type of virus causes negative results in yield and total plant loss. The extent of damage depends largely on the presence of soil already contaminated with the virus strain, high temperatures, high levels of inert gases such as nitrogen, and even light intensity [42].

Ornamental crops, which make up a large part of the agricultural market in countries such as Colombia, are no strangers to these viruses. In this case, one of the most important pathogens is tulip streak virus (TBV), also known as lily mosaic virus. Infections with this virus affect physical characteristics such as leaf cell deterioration, chlorosis, leaf discolouration, leaf shrinkage, necrosis and leaf deformation. TBV is mainly transmitted by aphids and affects a wide range of bulb flowers, causing economic losses in the millions, especially in Europe [43]. CMV is another virus affecting ornamental crops, including *Alstroemeria* spp. species, *Dendrobium, Galdiolus, Iris* spp., *Lilium* spp., *Dianthus* spp.

While the global economic impact of mosaic viruses is difficult to estimate (due to under-reporting and under-diagnosis), it is clear that they cause major losses to the entire agricultural sector, both in food and ornamental crops. Viruses such as MDMV, SCMV or wheat streak mosaic virus (WSMV) can affect up to 75-80% of crops, and economic losses can run into billions of dollars (e.g. losses of between $1.2 and $2.5 billion annually due to cassava mosaic virus in Africa) [3]. Mosaic viruses therefore pose a risk not only to agricultural economies but also to food security in many regions of the world, particularly in developing countries [12,13]. This highlights the importance of early detection and prevention (see figure 6).

Figure 6. Symptoms of sugar cane mosaic virus on sugar cane plants [40]

a) Healthy sugarcane plant; b-d) sugarcane with different degrees of infection by sugarcane mosaic virus [40]

Diagnosis and management

Diagnosis

The diagnostic methods traditionally used to identify and control viruses in different crops were based on determining the level of infectivity in different host organisms, called indicator plants. However, this method was expensive to produce. For this reason, most biotechnology laboratories use serological (ELISA) and molecular (molecular hybridisation and PCR) techniques, which require less investment and are highly effective. Serological techniques are based on the use of antibodies that allow the identification of pathogens, while molecular techniques aim to capture the nucleic acids of the virus, either by molecular hybridisation or by PCR, which consists of the exponential amplification of DNA fragments, so that from a few copies of a molecule, multiple copies are obtained, which can be observed by electrophoresis and appropriate staining [44].

In recent years, next-generation sequencing (NGS) technologies have revolutionised plant virus diagnostics. NGS is an efficient and relatively inexpensive method for generating large amounts of genetic data and studying the viral genome. This has led to the development of plant virus diagnostic techniques that do not require prior knowledge of the viral genome. However, despite progress, diagnostic techniques still require further development in the fields of bioinformatics and metagenomics to increase their accuracy. Over time, it is expected that diagnostics will become increasingly effective, widespread and accessible, particularly for developing countries [45].

Management

Given the widespread damage caused by mosaic viruses in vegetable crops and the lack of a cure or treatment, many research projects are looking at ways of controlling and managing these viruses, either through resistant varieties or the use of beneficial organisms. From this perspective, research into plant pathogens is a survival mechanism for agriculture and a way of ensuring food security in many regions of the world. For example, between 2005 and 2006, Sotelo [46] conducted a trial in Chile to determine the effect of MDMV on maize seedlings that had previously been treated with applications of beneficial fungi such as *Trichoderma* spp. and *Bacillus* spp., which act as a barrier to the development of pathogens in seedlings. Approximately ninety days after virus inoculation, various analyses were carried out to determine weight, average plant size and cellular composition to determine the effectiveness of the treatment and reduction in symptoms. At the end of the trial, it was possible to evaluate that the plants treated with *Bacillus* spp. had a positive result in the reduction of the pathogen [46].

The intricate tapestry of mosaic viruses, woven by their diversity and the myriad methods through which they propagate, necessitates a strategic approach rooted in phytosanitary control. To navigate this complex landscape, vigilance through monitoring and early detection becomes the cornerstone upon which effective control stands. Such meticulous oversight ought to extend to regional levels, where the insights garnered serve as vital intelligence for phytosanitary authorities entrusted with safeguarding our crops. It is within this context that the foundation for management strategies takes root, preempting the pathogen's advance. The linchpin of mosaic virus control lies in the initial thwarting of its expansion, achieved through the decisive act of eradicating all afflicted plants. This initial defense, however, only marks the genesis of our comprehensive countermeasure. Variability in mosaic viruses demands tailored tactics, prompting the subsequent execution of measures such as eradicating vectors of the virus, be they aphids, whiteflies, or other carriers. Further augmentation of our defense finds manifestation in the cultivation of plant varieties fortified with resilience against these viral onslaughts.

Yet, when the tools of diagnosis falter in the face of uncertainty, the prudent course remains isolation, and if warranted, the considered obliteration of the potentially infected plant. It is a somber but necessary act, undertaken to preclude the dissemination of a possible viral affliction. In essence, mosaic virus control is a symphony of strategies, orchestrated in harmony with the unique intricacies of each viral manifestation. From vigilant surveillance and astute detection to the resolute culling of infected hosts, and the intricate choreography of obliterating vectors, this multifaceted approach stands as our bulwark against the threat of mosaic viruses.

Conclusion

In a world where agriculture plays a crucial role in food supply and the economy, a thorough understanding of mosaic viruses and their effects is essential. Through this comprehensive analysis, we have unravelled the complexity of these pathogens, their symptomatic similarities and their potential threat to food and ornamental crops in modern agriculture.

From identification to diagnosis and management, we have explored the different stages of dealing with the presence of these viruses in agricultural fields. As we delve deeper into the subject, it becomes clear that the lack of effective treatment is a major challenge that we need to address. Not only do mosaic viruses cause similar symptoms in different crops, they can also cause significant economic losses.

The scale of their impact is not limited to the boundaries of an agricultural parcel; their reach extends to the economic and food stability of entire regions. The imbalance that these viruses can cause is a wake-up call for governments, especially in developing countries, to take decisive action. The implementation of epidemiological surveillance programmes and the training of local farmers are essential steps to prevent infection and mitigate the harmful consequences.

In the specific case of Colombia, the need to provide guidance and support to farmers facing these challenges is evident. The lack of training and resources to deal with mosaic virus situations is a problem that needs to be urgently addressed. The establishment of regional diagnostic strategies and early control measures is essential to prevent the spread and outbreak of epidemics that could devastate crops and the agricultural economy.

The role of the plant trade is also crucial in this journey towards more effective management of mosaic viruses. Awareness of the need to quarantine and destroy infected plant material can make a difference in preventing the spread of these viruses. This will not only ensure plant health, but also consumer confidence in agricultural products. In summary, our comprehensive analysis has led us to understand the urgent need for concerted action. Knowledge of mosaic viruses, their impact and prevention and control measures are essential to ensure food security and economic stability. By working together, the public and private sectors, and empowering farmers with information and training, we can build a more resilient and prosperous agricultural future where the threat of mosaic viruses is met with determination and wisdom.

Consent for publication

The authors read and approved the final manuscript.

Competing interest

The authors declare no conflict of interest. This document only reflects their point of view and not that of the institution to which they belong.

Author details

John Edinson Herrera Galvez

Environmental Engineer from the Unidad Central del Valle del Cauca-UCEVA, Colombia. Master in Neuropsychology and Education from the International University of La Rioja Spain, HSEQ Auditor, with studies in Pedagogy from the University Minuto de Dios. He has worked as an academic coordinator in different institutions, external consultant for day-care centres in the Colombian territory for the certification of their operation, as a research consultant for neuropsychology and engineering masters in different universities. His research has focused on environmental issues, which are of great importance for current legislation and educational integration in Colombia. Civil servant in urban and regional planning.

Felipe Bravo-Osorio

He holds a doctorate in philosophy from the University of Paris Sorbonne, a master's degree in logic and philosophy of science from the same university, and a master's degree in international studies from the University Sorbonne Nouvelle. He has worked as a university professor and researcher in Colombia and France. His publications focus on the philosophy of ecology, environmental ethics, philosophy of mathematics and education.

References

[1] Rizzo DM, Lichtveld M, Mazet JAK, Togami E, Miller SA. Plant health and its effects on food safety and security in a One Health framework: four case studies. One Health Outlook 2021; 3:6. https://doi.org/10.1186/s42522-021-00038-7

[2] Roig Vila D. Towards sustainable diets: a multidisciplinary approach. Nutr Hosp 2020; 37:2, 43-46. https://doi.org/10.20960/nh.03356

[3] Makkar GS, Bhatia D, Suri KS, Kaur S. Insect resistance in Rice (*Oryza sativa* L.): overview on current breeding interventions. Int J Trop Insect Sci 2019; 39:259–72. https://doi.org/10.1007/s42690-019-00038-1

[4] Bacca M, Higuita M, Restrepo A, Gallo Y, Marín M, Gutiérrez P. Analysis of viruses infecting Cape gooseberry (*Physalis peruviana* L.) in southwestern Antioquia (Colombia) suggests a new member of the genus Trichovirus. Archives of Phytopathology and Plant Protection 2023; 56:647–63. https://doi.org/10.1080/03235408.2023.2216342

[5] Hilaire J, Tindale S, Jones G, Pingarron-Cardenas G, Bačnik K, Ojo M, et al. Risk perception associated with an emerging agri-food risk in Europe: plant viruses in agriculture. Agric Food Secur 2022; 11:21. https://doi.org/10.1186/s40066-022-00366-5

[6] Patil BL. Plant Viral Diseases: Economic Implications. Encyclopedia of Virology, Elsevier; 2021, 81–97. https://doi.org/10.1016/B978-0-12-809633-8.21307-1

[7] Dias C, Mendes L. Protected Designation of Origin (PDO), Protected Geographical Indication (PGI) and Traditional Speciality Guaranteed (TSG): A bibiliometric analysis. Food Research International 2018; 103:492–508. https://doi.org/10.1016/j.foodres.2017.09.059

[8] Mehetre GT, Leo VV, Singh G, Sorokan A, Maksimov I, Yadav MK, et al. Current Developments and Challenges in Plant Viral Diagnostics: A Systematic Review. Viruses 2021; 13:412. https://doi.org/10.3390/v13030412

[9] Jeger M, Beresford R, Bock C, Brown N, Fox A, Newton A, et al. Global challenges facing plant pathology: multidisciplinary approaches to meet the food security and environmental challenges in the mid-twenty-first century. CABI Agriculture and Bioscience 2021; 2:20. https://doi.org/10.1186/s43170-021-00042-x

[10] Sieiro Miranda G, González Marrero A, Rodríguez Lema E, Rodríguez Regal M. Efecto de los macroelementos primarios en la susceptibilidad a enfermedades. Centro Agrícola 2020; 47:66–74. http://scielo.sld.cu/pdf/cag/v47n3/0253-5785-cag-47-03-66.pdf.

[11] Thresh JM. The Impact of Plant Virus Diseases in Developing Countries. Virus and Virus-like Diseases of Major Crops in Developing Countries, Dordrecht: Springer Netherlands; 2003, 1–30. https://doi.org/10.1007/978-94-007-0791-7_1

[12] Uke A, Tokunaga H, Utsumi Y, Vu NA, Nhan PT, Srean P, et al. Cassava mosaic disease and its management in Southeast Asia. Plant Mol Biol 2022; 109:301–11. https://doi.org/10.1007/s11103-021-01168-2

[13] Navarro JA, Sanchez-Navarro JA, Pallas V. Key checkpoints in the movement of plant viruses through the host, 2019, 1–64. https://doi.org/10.1016/bs.aivir.2019.05.001

[14] Elena SF, García-Arenal F. Plant Virus Adaptation to New Hosts: A Multi-scale Approach, 2023, 167–96. https://doi.org/10.1007/978-3-031-15640-3_5

[15] Mo Q, Lv B, Sun Y, Wu X, Song L, Cai R, et al. Screening and production of dsRNA molecules for protecting Cucumis sativus against Cucumber mosaic virus through foliar application. Plant Biotechnol Rep 2022; 16:409–18. https://doi.org/10.1007/s11816-022-00750-4

[16] McLeish MJ, Fraile A, García-Arenal F. Evolution of plant–virus interactions: host range and virus emergence. Curr Opin Virol 2019; 34:50–5. https://doi.org/10.1016/j.coviro.2018.12.003

[17] Morales Soto A, Lamz Piedra A. Métodos de mejora genética en el cultivo del frijol común (*Phaseolus vulgaris* L.) frente al Virus del Mosaico Dorado Amarillo del Frijol (BGYMV). Cultivos Tropicales 2020;41: e10. http://scielo.sld.cu/pdf/ctr/v41n4/en_1819-4087-ctr-41-04-e10.pdf

[18] Scholthof K-B. Tobacco mosaic virus. Plant Health Instructor 1997. https://doi.org/10.1094/PHI-I-2000-1010-01

[19] Jacquemond M. Cucumber Mosaic Virus, 2012, 439–504. https://doi.org/10.1016/B978-0-12-394314-9.00013-0

[20] Morozov SY, Agranovsky AA. Alphaflexiviruses (Alphaflexiviridae). Encyclopedia of Virology, Elsevier; 2021, 140–8. https://doi.org/10.1016/B978-0-12-809633-8.21526-4

[21] Creager ANH. Tobacco Mosaic Virus and the History of Molecular Biology. Annu Rev Virol 2022; 9:39–55. https://doi.org/10.1146/annurev-virology-100520-014520

[22] Saunders K, Thuenemann EC, Peyret H, Lomonossoff GP. The Tobacco Mosaic Virus Origin of Assembly Sequence is Dispensable for Specific Viral RNA Encapsidation but Necessary for Initiating Assembly at a Single Site. J Mol Biol 2022; 434:167873. https://doi.org/10.1016/j.jmb.2022.167873

[23] Gutiérrez P, Rivillas A, Tejada D, Giraldo S, Restrepo A, Ospina M, et al. PVDP: A portable open source pipeline for detection of plant viruses in RNAseq data. A case study on potato viruses in Antioquia (Colombia). Physiol Mol Plant Pathol 2021; 113:101604. https://doi.org/10.1016/J.PMPP.2021.101604

[24] Hechavarria M. Genotipificación y fuentes de resistencia de los agentes causales de virus del mosaico y hoja amarilla de la caña de azúcar. Anales de La Academia de Ciencias de Cuba 2018; 8:1–6. https://revistaccuba.sld.cu/index.php/revacc/article/view/363/362

[25] Perales-Rosas D, Hernández-Pérez R, Guillén-Sánchez D, López-Martínez V, Alia-Tejacal I, Andrade-Rodríguez M, et al. Detection of sugarcane yellow leaf virus and sugarcane mosaic virus in sorghum (*Sorghum bicolor* (L.) Moench) in the state of Morelos, México. Scientia Agropecuaria 2018; 9:423–7. https://doi.org/10.17268/sci.agropecu.2018.03.14

[26] Uke A, Khin S, Kobayashi K, Satou T, Kim O-K, Hoat TX, et al. Detection of Sri Lankan cassava mosaic virus by loop-mediated isothermal amplification using dried reagents. J Virol Methods 2022; 299:114336. https://doi.org/10.1016/j.jviromet.2021.114336

[27] Tseliou E, Chondrogiannis C, Kalachanis D, Goudoudaki S, Manoussopoulos Y, Grammatikopoulos G. Integration of biophysical photosynthetic parameters into one photochemical index for early detection of Tobacco Mosaic Virus infection in pepper plants. J Plant Physiol 2021; 267:153542. https://doi.org/10.1016/j.jplph.2021.153542

[28] Melcher U, Lewandowski DJ, Dawson WO. Tobamoviruses (Virgaviridae). Encyclopedia of Virology, Elsevier; 2021, 734–42. https://doi.org/10.1016/B978-0-12-809633-8.21529-X

[29] Liu HW, Luo LX, Li JQ, Liu PF, Chen XY, Hao JJ. Pollen and seed transmission of Cucumber green mottle mosaic virus in cucumber. Plant Pathol 2014; 63:72–7. https://doi.org/10.1111/ppa.12065

[30] Xu Y, Zhang S, Shen J, Wu Z, Du Z, Gao F. The phylogeographic history of tomato mosaic virus in Eurasia. Virology 2021; 554:42–7. https://doi.org/10.1016/j.virol.2020.12.009

[31] Meena RP, Minipara D, Choyal P, Kalariya KA, Saran PL, Roy S. Detection and molecular characterization of cucumber mosaic virus infecting Tylophora indica (Burm. f. Merrill). J Appl Res Med Aromat Plants 2022; 30:100391. https://doi.org/10.1016/j.jarmap.2022.100391

[32] Iftikhar Y, Ullah MI, Sajid A, Bakhtawar F. Virus-vector interaction and transmission in plants. Plant RNA Viruses, Elsevier; 2023, 273–84. https://doi.org/10.1016/B978-0-323-95339-9.00011-9

[33] Singh S, Awasthi LP, Jangre A, Nirmalkar VK. Transmission of plant viruses through soil-inhabiting nematode vectors. Applied Plant Virology, Elsevier; 2020, 291–300. https://doi.org/10.1016/B978-0-12-818654-1.00022-0

[34] Osei MK, Adjebeng-Danquah J, Bediako KA, Melomey LD, Agyare RY, Annor B, et al. Origin, evolution and bottlenecks of geminiviruses. Geminivirus : Detection, Diagnosis and Management, Elsevier; 2022, 79–93. https://doi.org/10.1016/B978-0-323-90587-9.00033-X

[35] Liu HW, Luo LX, Li JQ, Liu PF, Chen XY, Hao JJ. Pollen and seed transmission of Cucumber green mottle mosaic virus in cucumber. Plant Pathol 2014; 63:72–7. https://doi.org/10.1111/ppa.12065

[36] Sangeeta, Kumar RV, Yadav BK, Bhatt BS, Krishna R, Krishnan N, et al. Diverse begomovirus-betasatellite complexes cause tomato leaf curl disease in the western India. Virus Res 2023; 328:199079. https://doi.org/10.1016/j.virusres.2023.199079

[37] Loesch-Fries LS. Alfalfa Mosaic Virus (Bromoviridae). Encyclopedia of Virology, Elsevier; 2021, 132–9. https://doi.org/10.1016/B978-0-12-809633-8.21328-9

[38] Zerbini FM, Ribeiro SG. Bean Golden Mosaic Virus and Bean Golden Yellow Mosaic Virus (Geminiviridae). Encyclopedia of Virology, Elsevier; 2021, 192–9. https://doi.org/10.1016/B978-0-12-809633-8.21237-5

[39] Xue B, Shang J, Yang J, Zhang L, Du J, Yu L, et al. Development of a multiplex RT-PCR assay for the detection of soybean mosaic virus, bean common mosaic virus and cucumber mosaic virus in field samples of soybean. J Virol Methods 2021; 298:114278. https://doi.org/10.1016/j.jviromet.2021.114278

[40] Kannan M, Ismail I, Bunawan H. Maize Dwarf Mosaic Virus: From Genome to Disease Management. Viruses 2018; 10:492. https://doi.org/10.3390/v10090492

[41] Luo Y, Qin C, Qiu H, Zhang X, Tang X, Luo X, et al. Novel microRNAs associated with the immune response to cucumber mosaic virus in hot pepper (*Capsicum annuum* L.). Physiol Mol Plant Pathol 2023; 124:101963. https://doi.org/10.1016/j.pmpp.2023.101963

[42] Verdin E, Wipf-Scheibel C, Gognalons P, Aller F, Jacquemond M, Tepfer M. Sequencing viral siRNAs to identify previously undescribed viruses and viroids in a panel of ornamental plant samples structured as a matrix of pools. Virus Res 2017; 241:19–28. https://doi.org/10.1016/j.virusres.2017.05.019

[43] de Kock M.J.D., Stijger CCMM, Pham KTK, Lemmers MEC, van Dam M. Non-persistent TBV transmission in correlation to aphid population dynamics in tulip flower bulbs. Acta Hortic 2011:191–7. https://doi.org/10.17660/ActaHortic.2011.901.24

[44] Konakalla NC, Masarapu H, Voloudakis AE. Molecular biology and management of tobacco mosaic virus. Plant RNA Viruses, Elsevier; 2023, 173–91. https://doi.org/10.1016/B978-0-323-95339-9.00005-3

[45] Shanker AK, Bhanu BD, Alluri A, Rajah N, Chavez R, Maheswari M. Chloroplast evolution and genome manipulation. Climate Change and Crop Stress, Elsevier; 2022, 411–40. https://doi.org/10.1016/B978-0-12-816091-6.00001-8

[46] Renukadevi P, Sangeetha B, Malathi VG, Nakkeeran S, Satya VK. Enigmatic emergence of seed transmission of geminiviruses. Geminivirus : Detection, Diagnosis and Management, Elsevier; 2022, 285–306. https://doi.org/10.1016/B978-0-323-90587-9.00003-1